Fault Identification in an Electro-Hydraulic Actuator and Experimental Validation of Prognosis Based Life Extending Control

V. MAHULKAR, H. MCGINNIS, M. DERRISO AND D. E. ADAMS

ABSTRACT

In this paper we present an application of fault identification and control reconfiguration in the context of a high performance aircraft. A second order divided difference filter is used to identify an internal leakage fault in an electro-hydraulic actuator found in the aircraft elevator. The identified fault information is then utilized in the formulation of an aircraft systems model for prognosis-based control. An optimization based reconfiguration strategy is presented to minimize degradation of the fault in presence of performance, actuation, and mission constraints. The strategy is then validated through Hardware-in-the-Loop Simulations.

INTRODUCTION

Modern technological systems rely heavily on sophisticated control systems to meet increased safety and performance demands. This reliance on control is particularly prevalent in safety critical applications, such as spacecraft, aircraft, nuclear power plants, chemical plants processing hazardous materials etc., where unattended and minor faults could potentially develop into catastrophic failures if maintenance is not performed in a timely and proper manner. By compensating for faults to some degree, conventional closed loop feedback control design for a process plant or air vehicle system may prevent that fault from being observed and will eventually develop into a control loop malfunction resulting in unsatisfactory performance (even instability). Hence, there is a requirement to identify the faults as soon as they occur and modify the control strategy to ensure stability and performance [1].

Most of the existing research in the literature is centered around the objective of recovering as much of the pre-fault system performance as possible [2]. Some of

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these approaches assume total failure of the subsystem (actuator, sensor etc.) and then take one of two actions: (a) replace the failed components by their analytical or physical redundant counterparts, or (b) completely remove the failed components from the plant model. If the design objective is to restore the original performance of the system given faults in the subsystem components as stated above, then an unsustainable level of performance may be required from other (healthy) subsystems. This type of reconfiguration is not optimal because extreme performance requirements may further damage the system, and a faulty actuator may still be able to provide useful function. Some authors (e.g. Zhang et al. [3]) have considered the problem of reconfiguration of a partially operational actuator; however, there is a lack of analysis in the literature on the effect of reconfiguration on the faulty actuator. In other words, there is no analysis on the rate of degradation of the actuator due to modified actuation demands as a result of the reconfiguration.

APPROACH

The block diagram of the proposed approach is shown in Figure 1. The plant contains the models for the aircraft and the actuator. The controller provides signals to the actuator in order to achieve objectives set by the mission planner. Faults in aircraft such as hydraulic actuators are identified by the fault identification block. The prognosis module gives information about how the fault will progress based on the current degradation level and the mission profile. This prognosis information is then used by the controller reconfiguration and flight path optimizer to minimize degradation while achieving the best possible performance.

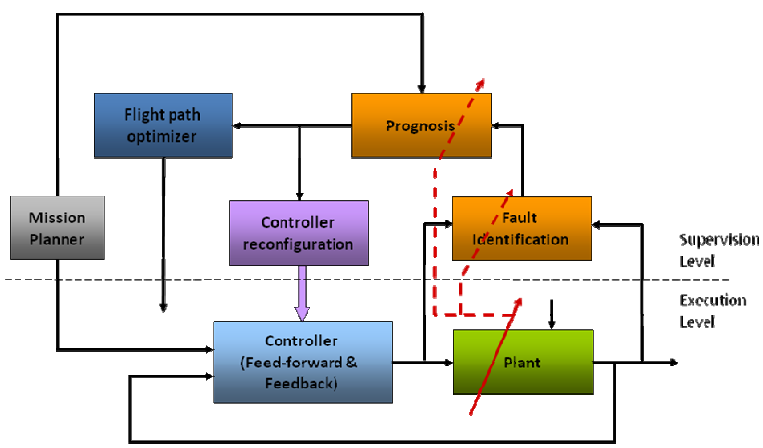


Figure 1: Approach

MODELS

This section gives a brief description of the models used in the modeling environment. A full nonlinear 6 d.o.f. model of a high performance aircraft is developed using Simulink. This model is then linearized about an operating point of

$10000\,ft$ altitude and $500\,ft/s$ velocity to obtain a simplified aircraft model in the longitudinal plane.

$$\begin{aligned} \dot{x} &= Ax + Bu \qquad & x &= \begin{pmatrix} h & \theta & v_t & \alpha & q \end{pmatrix} \\ y &= Cx \qquad & u &= \begin{pmatrix} \delta_t & \delta_e \end{pmatrix} \end{aligned} \tag{1}$$

where h is the altitude, θ is the pitch, v_t is the velocity, α is the angle of attack, q is the pitch rate, δ_t is the thrust, and δ_e is the elevator deflection. This model is connected to a simple first order model for thrust and a nonlinear hydraulic actuator model as given in Eq.(2) with internal leakage:

$$\begin{aligned} & m\ddot{x}_l = P_l A - b\dot{x}_l - F_{fc}(\dot{x}_l) + \tilde{f}(t, x_l, \dot{x}_l) \\ & \frac{V_t}{4\beta_e}\dot{P}_l = -A\dot{x}_l - Q_{leak} + Q_l \\ & Q_l = \frac{C_d w}{\sqrt{\rho}} x_v \sqrt{P_s - \operatorname{sgn}(x_v) P_l} \qquad Q_{leak} = C_{tm} a_{leak} \sqrt{P_l} \end{aligned} \tag{2}$$

where x_L is the displacement of the piston, $P_L = P_1 - P_2$ is the load pressure of the cylinder, A is the ram area of the cylinder, F_{fc} represents the modeled Coulomb friction force, $\tilde{f}$ represents the external disturbances such as unmodeled friction forces, C_{tm} represents the coefficient of the total internal leakage of the cylinder, x_v is the displacement of the spool of the directional proportional valve, Q_L is the load flow. More details on the terms in the dynamics equations can be found in [4]. F_L represents the aerodynamic forces acting on the actuator and are calculated as [5]:

$$F_l = 2K_L \bar{q} C_h(\alpha, \delta) M^*(M, \delta) \tag{3}$$

C_h is the nonlinear hinge coefficient which depends on α and the control surface deflection δ. $\bar{q}$ is the dynamics pressure and M is the mach number. The degradation model is an empirical model for the wear rate of a PTFE material seal. It is given as:

$$\begin{aligned} & g_r = f(\dot{x}_l) \ \ \mathrm{mm^3/N/m} \\ & w_r = g_r d_l F_L \qquad a_{leak} \propto w_r \end{aligned} \tag{4}$$

CONTROL

The aircraft control structure has two main loops: the velocity loop and the altitude loop. The velocity loop is controlled with a simple lead compensator where as the altitude loop is controlled using a cascaded PI control with stability augmentation and angle of attack feedback:

$$u_t = \frac{K_{vi}}{s+30} e_v + u_{t_{ff}}, \qquad u_e = -K_{q_p} q - K_{\alpha_p}\alpha - \left(\frac{K_{\theta_i}}{s} + K_{\theta_p}\right)\left(\left(\frac{K_{hi}}{s} + K_{h_p}\right)(e_h) - \theta\right) + u_{e_{ff}} \tag{5}$$

The position control for the actuator is achieved by generating a reference force trajectory based on the reference position trajectory. A Lyapunov based control design is then used to develop a control structure to track the reference force trajectory. The reference force trajectory and the control input are given in Eq. (6):

$$F_d = m\ddot{x}_d - K_{vs}(\dot{x}_l - \dot{x}_d) - K_{ps}(x_l - x_d) + \bar{F}_{fc}$$

$$u = \frac{x_v}{k_v} = \frac{1}{k_v}\frac{1}{z}\left(\frac{4\beta_e}{V_t}A^2\dot{x}_l - K_{fs}(F - F_d) + \dot{F}_d\right),\ z = \frac{C_d w}{\sqrt{\rho}}\frac{4\beta_e}{V_t}A\sqrt{P_s - \mathrm{sgn}(x_v)P_L} \tag{6}$$

RESULTS AND CONCLUSION

Fault Identification

The states and the internal leakage fault in the hydraulic actuator are identified using a second order divided difference filter (DDF) [6]. The discrete form of the actuator equations are given in Eq. (7):

$$\begin{aligned}
x_1(k+1) &= x_1(k) + T_s x_2(k) + v_1(k) \\
x_2(k+1) &= x_2(k) + T_s\theta_1\left(x_3(k) - \bar{b}x_2(k) - \bar{F}_{fc}\right) + \theta_2 + x_6(k) + v_2(k) \\
x_3(k+1) &= x_3(k) + T_s\theta_3\Big[-\bar{A}x_2(k) - x_5(k)\sqrt{x_3(k)}\,\mathrm{sgn}(x_3(k)) \\
&\qquad + \sqrt{\bar{P}_s - \mathrm{sgn}(x_4(k))x_3(k)}\,x_4(k))\Big] + v_3(k) \\
x_4(k+1) &= x_4(k) + T_s\left(\frac{-1}{\tau_v}x_4(k)\right) + \frac{\bar{K}_v}{\tau_v}u + v_4(k) \\
x_5(k+1) &= x_5(k) + v_5(k) \\
x_6(k+1) &= x_6(k) + v_6(k)
\end{aligned} \tag{7}$$

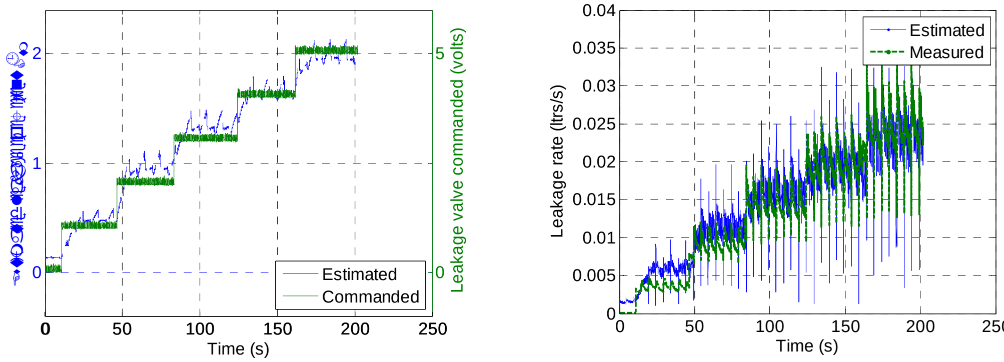
where $x_1,\ldots,x_4$ are states (position, velocity, load pressure and spool position), x_5 is the parameter appended as a state for unknown internal leakage fault and x_6 is the appended state for estimating friction. Vector $v(k)$ is the process noise covariance. It is important to estimate friction online because of the large uncertainty associated with offline friction estimation. Adding the friction parameter improves the estimation accuracy significantly. The process covariance, measurement noise covariance and the initial state estimate variance used for the estimation and fault identification are as follows:

$$\begin{aligned}
Q &= \mathrm{diag}\left(\begin{bmatrix}1\times10^{-2} & 1\times10^{-2} & 1 & 1\times10^{-2} & 6\times10^{-6} & 1\end{bmatrix}\right) \\
R &= \mathrm{diag}\left(\begin{bmatrix}1\times10^{-6} & 1\times10^{-2} & 1\times10^{7} & 1\times10^{-2}\end{bmatrix}\right) \\
P &= \mathrm{diag}\left(1\times10^{2}\begin{bmatrix}1 & 1 & 1 & 1 & 1 & 1\end{bmatrix}\right)
\end{aligned} \tag{8}$$

Figure 2(a) shows the results of fault identification with step changes in the leakage levels. The actual measured flow rate is shown in Figure 2(b). As can be seen, very small leakage rates are difficult to identify. However, as leakage becomes greater than $.01 ltrs/s$ the fault levels are distinctly identified with a constant ratio between the voltage to the leakage valve and the identified coefficient.

Reconfiguration for Life Extension

After the aircraft and the actuator models are combined, the gains of the aircraft controller are tuned through optimizing the following objective function with constraints:



(a) (b)

Figure 2: Fault identification for step changes in the leakage level and measured v/s estimated flow rate

$$\min J = w_r(t_f)^T W w_r(t_f) + \int_0^{t_f} e_y^T Q e_y \, dt \tag{9}$$

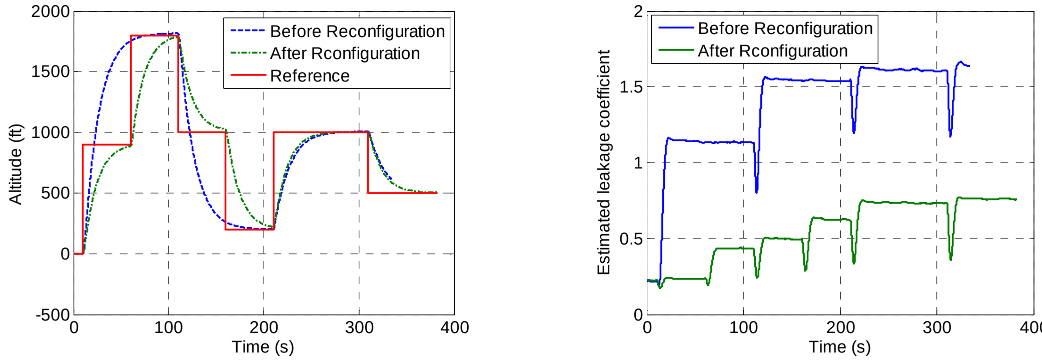
$$\begin{aligned}
\text{subject to } \dot{x} &= f(x,u,t) && \text{system equations} \\
u &\in [u_{min} \quad u_{max}] && \text{input constraints} \\
x &\in [x_{min} \quad x_{max}] && \text{state limits} \\
\lambda &\in [\lambda_{min} \quad \lambda_{max}] && \text{other constraints} \\
x(0) &= x_0 && \text{initial conditions}
\end{aligned} \tag{10}$$

where w_r is the degradation of the actuator, t_f is the final time, e_y is the output error. Eq. (10) includes constraints on degradation level, time domain constraints such as rise time t_r, settling time t_s, maximum overshoot m_p etc. The first half of the objective function as given in Eq.(9) ensures that the degradation at the end of the mission is minimized and the second part ensures that the system follows the trajectory as closely as possible. Using this objective function, it is possible to generate a trade-off between the degradation level and the maximum performance attainable. The reconfiguration supervisor uses a mixed integer programming optimization strategy to find the best possible response while keeping the degradation for a particular mission below a pre-specified level. This can also be interpreted as minimizing the degradation given the mission and performance constraints. This is achieved using the following objective function:

$$\min_{t_r, n_{steps}} J = \sum_{i=1}^{n_{steps}} t_r(h(i)) \tag{11}$$
$$\text{subject to } w_r(t_f) \le w_{r,commanded}$$

The optimization minimizes the sum of rise times (performance) of the step response of the aircraft. This optimization is also performed over the number of steps in the trajectory (assuming that the trajectory is supplied in terms of step changes in altitude for a longitudinal aircraft model).

The step response is used as a performance measure in this case so that the aircraft can get to the desired altitude as fast as possible. This measure gives a buffer in case there is fault allowing more time to get to the desired waypoint. Figure 3 shows the response of the system before and after reconfiguration.



(a) (b)

Figure 3: Response before and after reconfiguration

The reconfiguration strategy modifies the waypoint map by adding two additional waypoints – one between original waypoints 1 and 2; and the second between original waypoints 2 and 3. Further the performance times for the entire mission profile were modified as given in Table 1. This results in reduction in degradation by almost a factor of 2 as seen in Figure 3 within first 350s of the experiment.

Table 1: Reference and response before and after reconfiguration

Ref Before	1800		200		1000	500	1500	100	300	800	1300	600
Ref After	900	1800	1000	200	1000	500	1500	100	300	800	1300	600
Resp Before	19.5		19.5		19.5	19.5	19.5	19.5	19.5	19.5	19.5	19.5
Resp After	24.4	24.4	23	23	23	20	28	20	19.5	20	20	20

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